1974

Processing of spatial information

Axel Armin Goetz
Iowa State University

74-15,427

GOETZ, Dr. Med., Axel Armin, 1940-
PROCESSING OF SPATIAL INFORMATION.

Iowa State University, Ph.D., 1974
Psychology, experimental

University Microfilms, A XEROX Company, Ann Arbor, Michigan

Processing of spatial information

by

Axel Armin Goetz

A Dissertation Submitted to the

Graduate Faculty in Partial Fulfillment of

The Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Major: Psychology

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

Signature was redacted for privacy.

For the Graduate College

Iowa State University
Ames, Iowa

1974

TABLE OF CONTENTS

INTRODUCTION

If thinking involves the processing of information it is important to know how information can be represented in memory, how it is represented during processing, and what the properties of these processes are.

One of the first to investigate alternatives to linguistic representations of information was Sir Francis Galton. Upon evaluating the returns of a questionnaire he had sent to "persons of distinction in various kinds of intellectual work", he concluded, apparently somewhat to his own surprise: "that scientific men as a class have feeble powers of visual representation. There is no doubt whatever on the latter point, however it may be accounted for" (1880, p. 304).

Maybe visualizing the morning breakfast table, the task Galton required his correspondents to perform, involved too trivial a subject to be remembered by these illustrious minds. The implication of his conclusion, that imaginal representation of information may be inconsequential for thinking or even incompatible with it, has certainly not gone unchallenged. A compatriot of Galton began his article on the objective study of mental imagery with the words: "Images are the material of thought..." (Short, 1953), and Jacques Monod, an outstanding scientific confrere of his, speculated:

I am sure every scientist must have noticed how his

> mental reflection, at a deeper level, is not verbal: to be absorbed in thought is to be embarked upon an imagined experience[1], an experience simulated with the aid of forms, of forces, of interactions which together only barely compose an "image" in the visual sense of the term.... However, it is not then that the significance of the simulated experience comes clear, but only when it has been enunciated symbolically (1972, p. 155 f.).

This abstract representational system that Monod characterized negatively - not verbal, hardly visual - could be called spatial, in the sense that it allows the coding of the relative positions of elements (form) and the change of these positions as a consequence of outside factors (forces) or the functional relationships between the elements (interactions). In these terms, Monod's introspections would be consistent with Cooper and Shepard's (1973) statement "that the most important and general divisions in cognitive processes are between entire coherent systems -- perhaps most clearly the spatial and the linguistic systems" (p. 79).

Such a distinction would be supported by the apparent separate localization of these two representational systems in the two hemispheres of the human brain (e.g. Kimura, 1973; Gross, 1972; Galin & Ornstein, 1972; Taylor, 1972; Geffen, Bradshaw, & Wallace, 1971; Gazzaniga, Bogen & Sperry, 1965). While no single study by itself proves that the two representational systems are separated anatomically, a wide

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[1]Emphasis Monod's

variety of stimulus materials, paradigms, and measures yield results consistent with this notion.

More important, several recent studies, correlational as well as experimental, converge in their conclusion that there are mental tasks which induce subjects to encode, store, manipulate, and retrieve spatial information.

Gavurin (1967) correlated scores on a spatial abilities test (Revised Minnesota Paper Form Board) with a measure of performance in a six-letter anagram solution task. One group of Ss was permitted to only mentally manipulate the letters with a resulting correlation of $r = .54$ between test and anagram scores. The Ss in another group were permitted to concretely manipulate the letters. Here the correlation between the two measures was $r = -0.18$. Making the visual mode available may have relieved the Ss of the necessity to mentally manipulate information.

A similar paradigm was used by Frandsen and Holder (1969) who used the DAT test of Spatial Reasoning and a variety of verbal problem solving tasks, which included syllogisms, time-rate-distance problems, and logical deduction problems. They found a correlation between spatial test scores and verbal problem solving scores of $r = .56$. This correlation decreased in magnitude but remained statistically significant after partialing out DAT Verbal Reasoning scores. Half of the Ss in each of the two extreme groups, in terms of performance on the spatial test, received instruction on diagramatic techniques of representing data and conditions in the verbal problems. In a problem solving post-test only the group low in spatial-visualization aptitude profited from instruction in diagramatic representation, reaching the performance level of the high-aptitude group, which did not show any reliable pretest-posttest change. Apparently, training in concrete diagraming techniques did not add to what the high-aptitude Ss could accomplish mentally.

A clue as to how spatial abilities may be related to the mental anagram solving task is provided by Furby (1971). While performance in nonsense anagram tasks correlated reliably with measures of spatial visualization, word anagram performance did not. The meaningful unit of a word provides a readily available means of organization of the to-be-manipulated letter sequence. This means of organization not being available in the nonsense condition, some Ss might have tried to store a visual-spatial representation of the letter string.

Such a visual-spatial representation of a sequence of symbols appears to have been used by Ss in a "keeping-track" task (Monty, 1968). Subjects were to observe and mentally tally the number of occurrences of each of four different stimuli or stimulus categories presented sequentially. Performance in this task was greatly facilitated if spatial encoding cues were provided, e.g. four adjacent windows, one for each class displayed with a constant class-window relationship. Error rates were more than twice as high when the class-window relationship changed randomly or the same stimulus sequence was displayed on one window. Monty and Karsh (1969) used this "spatial window" model in a keeping-track experiment involving auditory stimuli which were either pitch-ordered or unordered. Error rate was much higher for the unordered stimuli. The authors conclude that spatial encoding can play a role in short-term memory irrespective of the stimulus modality employed.

In an investigation of <u>S</u>s' performance on linear syllogisms DeSoto, London, and Handel (1965) find results consistent with their hypothesis that in reasoning about orderings of elements, people rely on spatial representations or thought models. According to this view, the premises are interpreted and combined in a unitary, visual-image representation in two-dimensional space. After positioning the to be compared elements in this representation on the basis of the premises, the conclusion is read out from the image. While supportive evidence for an image theory of propositional thinking is provided by Handel, DeSoto, and London (1968) and Huttenlocher (1968), it has been contested recently by Clark (1969), who proposes a linguistic theory on the basis of his own data. Wason and Johnson-Laird (1972) review evidence reconciling the two theories. Subjects unfamiliar with the task behave more according to the image theory, but after a few trials they appear to change to more efficient strategies which are consistent with the linguistic theory of propositional thinking.

Playing chess appears to be another task where the manipulation of spatial-relational information is crucial. Chase and Simon (1973) conclude on the basis of recall of briefly exposed chess positions that experienced players store a large number of patterns of chess pieces in long-term memory in terms of their spatial and functional relationships.

Several recent studies deal more specifically with the nature of spatial representations and the processes operating on them. Shepard and Metzler (1971) presented Ss with perspective line drawings of rectangular structures composed of cube elements extending in 3 dimensions. The Ss had to decide whether two simultaneously presented pictures represented the same structure in two versions differing in degree of rotation or whether the two line drawings could not be matched. Reaction time was found to be a linear function of rotational discrepancy between the two stimulus figures. For matching pairs, very nearly the same slopes obtained for rotation in the frontal and in the horizontal depth plane.

These data suggest the existence of an isotropic "working store" in which spatial representations can be mentally "rotated". In Shepard and Metzler's study speed of "rotation" averaged about 60 degrees per second. Data by Sekuler and Nash (1972) suggest that this variable may be a function of stimulus complexity. Cooper and Shepard (1973) presented line drawings of letters and digits as the to-be-compared stimuli in sequence. The two successive pictures differed in terms of degree of rotation of the stimulus symbol, and Ss had to decide whether the second symbol was the same as the first or its mirror image. Reaction time again was a monotonic function of rotational discrepancy, and in addition, of the duration of the interstimulus interval if advance information about the orientation of the second stimulus was given. Reaction times to an expected stimulus were approximately equal, regardless of whether the advance information was presented in the form of a visual outline of the stimulus already rotated to the orientation in which it was to appear, in the form of a visual outline of that stimulus in its upright position followed by an indication of the orientation in which it was to appear, or in auditory form. Further, Ss were able to mentally "rotate" an imagined letter, with speed of "rotation" paced by auditory cues, and thus maintain optimal readiness for the appearance of the second, visual stimulus.

These data suggest that mental images can be generated by Ss and that these images carry spatial information about shape and orientation of the imagined stimulus. This conclusion is supported by Hayes (1973), who, in addition, finds indications that generated images carry information about size.

While the potential importance of spatial representational systems for thinking processes is recognized, and while there are a number of highly ingenious studies investigating properties of spatial processing, this research, as Newell (1973) notes, does not add up to a coherent interpretation. While in many studies it appears plausible to assume that the results are due to spatial processing, there are no controls for verbal mediation. Further complications arise when visual stimulus representations are used and the possibility cannot be excluded that processing occurs on the basis of, or is influenced by, visual-perceptual codes. This problem appears to have been neglected consistently in theoretical as well as experimental studies. Commenting on this state of affairs, Pylyshyn (1973) finds it unsatisfactory "...that no consideration is given to the possibility that cognition may be "mediated" by something quite different from either pictures or words..." (p.4). That there is reason to distinguish visual from spatial processes is evident, e.g. from the work by Bitterman (1965).

However, there still is an almost complete lack of experimental evidence concerning some of the basic concepts of information processing in the spatial representational system: encoding, storage, organization, and retrieval.

Purpose of the Investigation

The four experiments reported here were designed to demonstrate the existence of a spatial mode of cognitive representation that is distinct from verbal or visual codes. For this purpose, a general paradigm was developed and tested for its suitability and flexibility to study various aspects of the processing of spatial information. In particular, it was attempted to show that information can be encoded spatially, stored, organized, retrieved after a long-term retention period, and manipulated within a complex task, in terms of a spatial code.

In order to isolate spatial processing, it had to be excluded that performance on the experimental tests was due to visual processing, verbal processing, or both. Visual processing was excluded as a contributing factor by avoiding the use of pictures as a mode of presentation, and of reproduction of the spatial figures by the Ss as mode of testing. Except for a recognition test in Experiment IV, Ss never saw a representation of the spatial stimuli they learned. The presentation of the stimulus material was entirely verbal. The nominal stimuli in all experiments were six, one-syllable direction words: up, down, right, left, in, out. Throughout this investigation, all experimental subjects received the following instructions, read by the experimenter, to imagine spatially extended figures on the basis of subsets of the six direction words:

> Your task in this experiment is to imagine an number of simple figures that I will describe to you and to memorize those figures. The figures look similar to this model (present model shown in Figure 1). Each figure has straight lines that are connected with right, or 90 degree angles. I will describe to you each figure in words so you can imagine it. The words I'll use are always selected from the following 6: "up, down, left, right, in, out". From your point of view the description of this (show model) figure e.g. would be: "left, down, out, left" (point in sequence of directions) or, if you read it out backward it would be: "right, in, up, right" (point in sequence of directions), from your point of view. That is, each word corresponds to a line and each line is connected with the previous line by a right angle. All lines have equal length. I want you to imagine all figures in the same orientation, so that "up-down" (point) refers to the vertical dimension, "right-left" (point) to the horizontal dimension, and "in-out" (point) to the depth dimension. Now, please describe this figure (present model in new orientation) in terms of the same direction words I have used, starting here (point to one end of the model), and again, starting there (point to opposite end of the model). For each figure you will learn, please keep in mind at which end its description starts. Now, let's try it without a model figure. I give you the directions and you tell me when you have constructed the figure in your mind. "Out, up, right, down, out". Please give me back the direction words describing this figure (S recalls). Now, start at the end-point of the figure and read out the directions backward. (Only if S recalls correctly: "in, up, left, down, in" at this point is this part of the instructions finished. If not, more examples are provided for training).

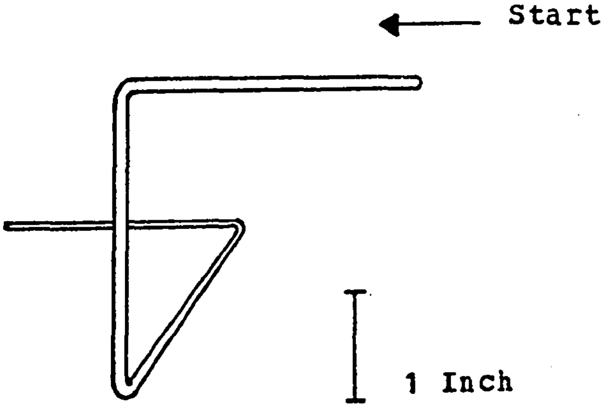

Figure 1. Perspective drawing of solder wire model, representing the stimulus figure "left, down, out, left".

Since presentation and testing were entirely verbal, the identical stimulus material could be presented to control groups, within identical time constraints and, under the null hypothesis, with identical expectations concerning test performance. The control Ss received instructions to learn the material in whatever way they preferred, without reference to the possibility of spatial representation. Any differences in performance would thus be attributable to the effects of the instructions. By inference, these differences would reflect the characteristics of spatial processing versus those of the spontaneously employed, most likely verbal, strategies of Ss. Thus, two different representational systems would be studied with the same nominal stimuli and within the same paradigms.

All experiments were intended to capitalize on properties that the imagined spatial stimuli possess but not their verbal counterparts. The first experiment was designed to test the hypothesis that a spatial code exists and is used under the experimental conditions chosen. Subjects learned one string of direction words at a time and recalled it after three seconds in either forward or backward order. Faster backward recall for the experimental than for the control group was expected if Ss in the former encoded the strings in terms of a spatial representation.

The second experiment tested the hypothesis that information can be stored in terms of a spatial representation. Again, one string was learned at a time, but recalled after a 6- or 18-second interval, filled with either a verbal or a spatial interference task. If experimental Ss showed better recall under verbal interference than controls, and vice versa under spatial interference, the hypothesis would be supported.

Experiment III attempted to demonstrate that the direction words in a string are organized into an integrated spatial stimulus under spatial instruction conditions. This would be inferred if subspan strings of different length would be learned and retained equally well.

Finally, Experiment IV was designed to test the hypothesis that spatial information can be retrieved after long periods of time and manipulated in ways unanticipated at the time of learning. Experimental and control subjects learned a paired-associate list and were either tested after one minute or one week for paired-associate and free recall, for recognition, and, in the experimental group, for their ability to mentally combine two spatial figures into one composite.

EXPERIMENT I

To be sure that the behavior of Ss in an experiment is a consequence of their processing spatial information, it is necessary to assume that the experimental task cannot be accomplished on the basis of any other but spatial information. This, in turn, requires the assumption that spatial information was originally encoded by the Ss.

Experiment I was designed to demonstrate that the stimulus material used in this study is encoded in terms of its spatial attributes if Ss receive mental imagery instructions (p. 10). The Ss received twenty trials in a modified Brown-Peterson short-term retention paradigm. Each trial consisted of presentation of a string of words, selected from the set (up, down, left, right, in, out) at a 2-sec. rate, a 3- sec. retention interval, and a period for recall. One half of the trials had 3-word strings, the other half 4-word strings. Two groups of Ss received the identical tape recorded presentation of the stimulus material and were expected to produce identical recall under the null hypothesis. The groups differed with regard to the instructions for learning the stimulus material. The experimental group (E) received instructions to spatially encode the stimulus material, i.e. to transform each string of direction words into an imagined spatial figure (p. 10). The control group (C) received standard verbal learning instructions (see Method section).

Two modes of recall were employed: Forward and backward recall. In the forward mode Ss would repeat the same words in the same order as presented. Correct backward recall would consist of transforming each direction word into its opposite term, e.g. "up" into "down" and, in addition, reversing the sequence of direction words. For example, the string "out, right, up" would in backward recall translate to "down, left, in". Forward recall should not pose any difficulty to either group. Group C Ss would simply recall from short-term memory, while group E Ss, given effective instructions, would be expected to read out the imagined stimulus figure. In backward recall, Ss in group E would do likewise, starting at the opposite end of the stimulus figure. In contrast, backward recall would be much more difficult for C subjects, who would have to apply two transformation rules while remembering the to-be-recalled information.

If Ss in the E condition do in fact encode the stimulus material spatially, forward and backward recall would involve the same processes, namely reading out an imagined stimulus figure. Recall performance should be equivalent for both conditions. However, in the C group, where recall is based on verbal processing, backward recall should be vastly inferior to forward recall. Thus, the experimental prediction would be an interaction of Instructions with Recall Mode. This interaction should be present in both dependent measures: Probability of correct recall and response latency. The response latency measure was added, since it was expected to be more sensitive than the recall probability measure, to help avoid problems of ceiling and floor effects, and to permit more precise predictions about performance in the four conditions. The lowest latencies would be expected in forward recall of the C group. More time would be required for reading out the spatial imagery figures than for dumping items from short-term memory, with forward recall slightly faster than backward recall, since verbal cues may still be available despite *Ss'* spatial encoding. By far the longest latencies should be found in the backward recall condition of the C group. Here a response can only be emitted after two successive stages of transformation of the stimulus material have been accomplished.

Method

Subjects. The 16 volunteer *Ss* from introductory psychology courses at Iowa State University were assigned to each of the instruction conditions according to a prearranged random schedule, with the restriction that the ratio of males to females must be constant across conditions. There were 5 females and 3 males in each instruction condition.

Materials and procedure. The strings of words used were subsets of the following set of direction words: "up, down, right, left, in, out". They were selected with regard to the spatial properties of the figures they describe. The 10, 3-word strings represented a random sample of the strings which describe the 24 possible 3-element spatial stimuli extending in all 3 dimensions. Of course, none of these figures is symmetrical. The 10, 4-word strings were derived from an analogous random sample of 3-element items. To each of these one element was added, such that the resulting stimulus figure would not be symmetrical and would not have two subsequent elements extending in the same dimension. The stimuli used are described in Table 3, Appendix A. The sequence of 3- and 4-element stimuli was randomized with the restriction that the first ten strings contained five of each type. The direction words were tape recorded for auditory presentation at a 2-sec. rate for the words within a string. Each string was followed by a silent 3-sec. interval, after which Ss were cued to recall either forward or backward. The cue for forward recall was the word "Go" which was followed by a 5-sec. recall interval, the cue for backward recall was the word "Back", followed by a 15-sec. interval. Both modes of recall were used equally often. They were sequenced randomly with the restrictions that 3- and 4-element stimuli would be represented equally often in both recall modes and that either mode of recall would not occur more than 3 times in a row.

Each S was tested individually. When a S, assigned to the E condition, reported to the experimental room, the spatial encoding instructions (p. 10) were read to him and, in immediate succession, the following instructions:

> You will hear a recording of short lists of direction words. Each list will either have 3 or 4 words, corresponding to figures with either 3 or 4 lines. Each list is preceded by the word "Ready". Whenever you hear "Ready", you know that a 3- or a 4-word list will follow. After the words of any single list you will be asked to do either one of the following two things: Number one: Just repeat the words as they were presented when you hear the word "Go". E.g. if you heard: "left, out, down, left", you would say "left, out, down, left". That's simple enough. Or, number two: Recall the list backward: Read out the figure you have imagined, beginning at the other end. E.g. if you heard: "out, down, left", recall: "right, up, in". If you are to recall backward, you will hear the word "Back" instead of "Go" after the words of the list. Before we start with the experiment, there will be some practice trials for you. I will do two things: record your answers and the time it takes you to find your answers. Please make sure your answers are correct. It is unimportant how fast you are, the important thing is to be correct. Do you have any questions? Would you now please tell me in your own words how the experiment is going to go, so I know you got the idea.

Control Ss were read the following instructions:

> This is an experiment about memorizing directions. You will hear a recording of short lists of words. I want you to listen to to these words and to repeat each list after a short pause. Each list will have either 3 or 4 words. The words are always selected from among the following six: "up, down, left, right, in, out". Each list is preceded by the word "Ready". Whenever you hear "Ready", you know that a 3- or 4-word list is to follow. After the words of any single list you will be asked to do either one of the following two things: Number one: Just repeat the words as they were presented when you hear the word "Go". E.g. if you

> heard: "left, out, down, left", you would say: "left, out, down, left". That's simple enough. Or, number two: Recall the list backwards: What was "down" is now "up", what was "up" is now "down", and the same way with "in, out, left, right". In addition, change around the order of the words. I.e., recall the first word last and the last word first, but, of course, in terms of their opposites. E.g. if you heard "out, down, left" you would recall: "right, up, in". If you are to recall a list backwards in this way, you'll hear the word "Back" instead of "Go". Before we start with the experiment there will be some practice trials for you. I will do two things; record your answers and the time it takes you to find your answers. Please make sure your answers are correct. It is unimportant how fast you are, the important thing is to be correct. Do you have any questions? Would you now please tell me in your own words how the experiment is going to go, so I know you got the idea.

After the six practice trials the tape recorder was stopped in order to clarify any questions S might have. The Ss' oral recall was recorded by E. In addition, E recorded the time between cueing for recall and onset of recall by means of a stopwatch.

Analyses. One point was scored for each string recalled completely and in correct order. The recall data were analyzed in a 2 x 8 x 2 x 2 (Instruction by Subjects by Recall Mode by Complexity) analysis of variance.

The latency data were subjected to reciprocal, square root, and logarithmic transformations. Among these, the logarithmic transformation produced the greatest homogeneity of variance. The log transformed data were analyzed in a 2 x 8 x 2 x 2 (Instruction by Subjects by Recall Mode by Complexity) analysis of variance. An analogous analysis with unequal cell frequencies was performed on the log transformed latencies for correct responses only.

Results and Discussion

Recall data. The prediction that E Ss would recall at a higher level than C Ss in the backward recall condition was borne out (Figure 2). The probability of correct backward recall was .81 for E and .68 for C Ss, $t(14) = 2.95$, $p < .05$. No such recall advantage was obtained in forward recall (.89, .86), there was no significant main effect of Instruction, and the predicted Instruction by Recall Mode interaction was not present.

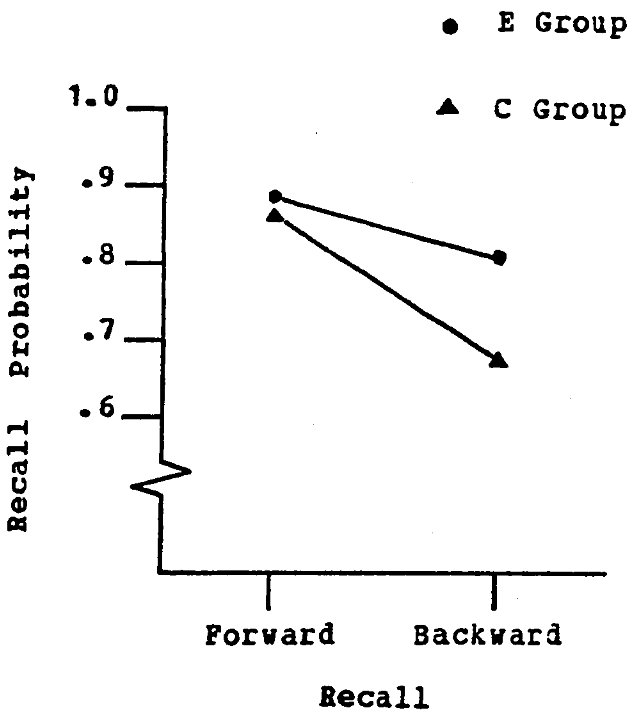

Figure 2. Probability of forward and backward recall.

The summary of the analysis of variance for the recall data is shown in Table 9, Appendix B.

Since the instructions for both groups advised Ss explicitly to emphasize precision of recall and to disregard E's recording time, the results may indicate that Ss followed this aspect of the instructions rather closely. However, if Ss did try to make sure that their responses were correct, differences in difficulty should appear in the latency measure.

Latency data. The analysis of the log transformed latencies for correct responses (Table 1) revealed the predicted interaction of Instruction with Recall Mode, $F(1,14) = 78.92$, $p < .001$.

While response latencies are not different for E and C Ss in forward recall, backward responses are considerably faster in the E than in the C condition. Figure 3 shows that this relationship holds for correct response latencies as well as for correct plus incorrect latencies. The summary of the analysis of the correct plus incorrect response latency data is shown in Table 10, Appendix B. Since the two analyses do not differ in any crucial aspect and latencies of correct responses pose less severe problems of interpretation, the discussion will be limited to correct response latency data.

Table 1. Summary of analysis of variance of log latency of correct responses only, Experiment I.

Source of variation	Degrees of freedom	Mean squares	F values
Instruction (Inst)	1	0.5745	3.038
Ss	14	0.1891	
Recall mode (Mode)	1	6.2560	432.678***
Inst x Mode	1	1.1411	78.924***
Mode x Ss	14	0.0145	
Complexity (Com)	1	0.0509	2.262
Inst x Com	1	0.0492	2.191
Com x Ss	14	0.0225	
Mode x Com	1	0.0016	0.094
Inst x Mode x Com	1	0.0075	0.429
Residual	186	0.0174	

*** $p < .001$

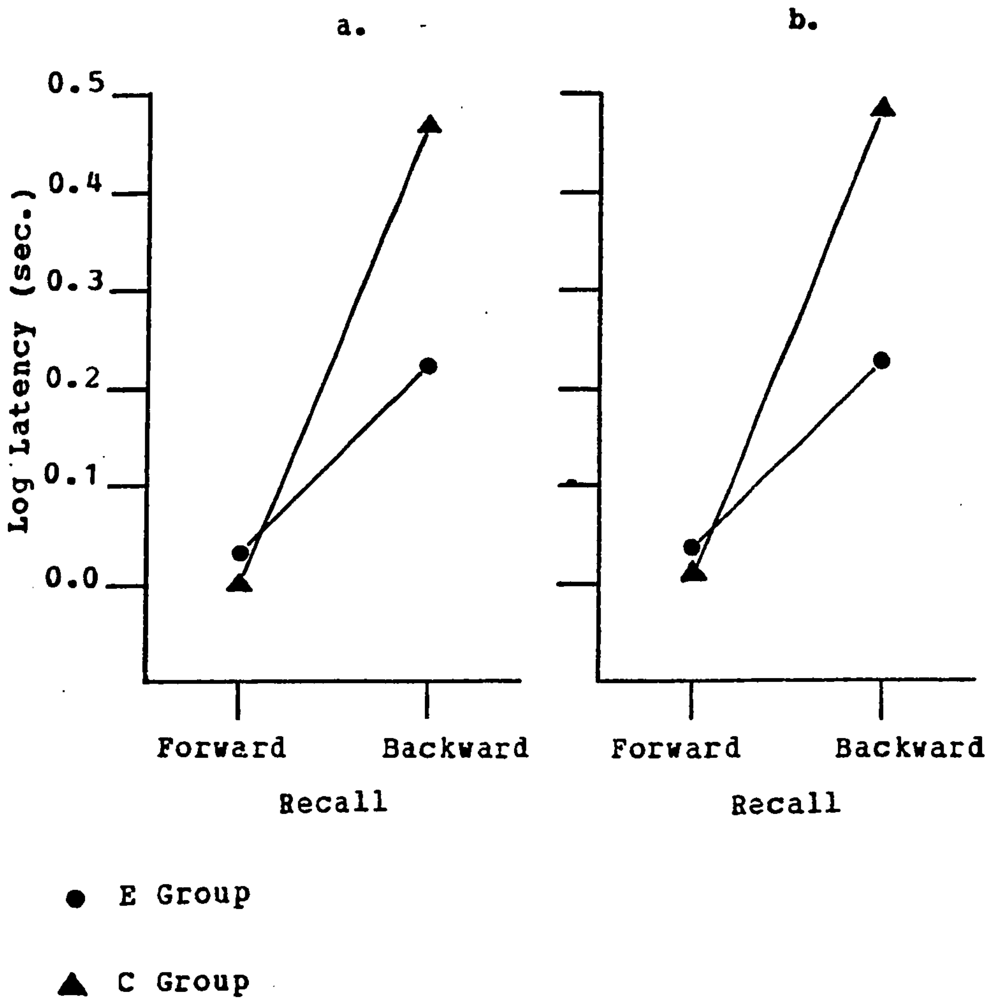

Figure 3. Latencies for forward and backward recall, a. correct responses only, b. correct and incorrect responses.

Although it can be assumed that there is a trade-off between accuracy and speed of response, the present data demonstrate that the faster responses of E Ss in the backward condition were not obtained at the expense of accuracy. Both dependent measures show E Ss to be superior in backward recall. This superiority is not trivial; while being more precise, E Ss are almost twice as fast (1.7 sec.) as C Ss (3.0 sec.) in backward recall.

The only difference in the experimental treatment of groups E and C was in terms of the instructions read to Ss. If it is assumed that the results obtained are due to the difference in instructions, this constitutes a case where E determined organization of information is clearly superior to Ss' own organizational strategies. However, Ss apparently do not use spatial encoding strategies consistently as the instructions for the E group suggest. If they did, forward and backward recall should be equally fast. Figure 3 shows that this is not so: forward recall is faster, $t(14) = 10.40$, $p < .001$. Whether some Ss encode spatially while others fail to do so or whether there is a verbal component involved in all Ss' processing of the stimulus information cannot be decided on the basis of the present data.

EXPERIMENT II

The results of Experiment I suggest that under different instructions Ss use different types of encoding for the same material. In particular, the finding that E Ss accomplish the transformations necessary for backward recall almost twice as fast as do C Ss, is most parsimoniously explained by assuming that the E Ss have recoded the stimulus words into spatial representations. However, it cannot be excluded that E Ss, guided by their instructions, invented nonspatial mediation schemes that were more efficient than those adopted spontaneously by C Ss.

Another interpretation is discussed by Hayes (1973). Since an image can be generated, it also can be regenerated. It may thus not persist as image at all, but be regenerated on the basis of an identifying code when needed in a problem solving or recall situation.

Experiment II was designed to test the hypothesis that Ss in the spatial instructions condition (group E) store a spatial representation of the stimulus material, while Ss in the control group (C) store a verbal representation.

The Ss received 32 trials in a Brown-Peterson short-term retention paradigm. Each trial consisted of the presentation of a string of 3 words selected from the set (up, down, left, right, in, out) at a 2-sec. rate, a retention interval filled with a distractor task, and a 10-sec. period for recall.

Half of the retention intervals were of 6 sec. duration, half of 18 sec. duration. Factorially combined with duration of the retention interval was the mode of the distractor task. Half of the intervals were filled with a verbally interfering task, half with a spatially interfering task. Two groups of Ss received the identical tape recorded presentation of the stimulus material and, under the null hypothesis, were expected to produce identical recall. The groups differed with regard to the instructions for learning the stimulus material in the same way as in Experiment I.

If E Ss store a spatial representation of the stimulus material, their recall performance should be higher than the C Ss' performance under verbal interference conditions. Conversely, C Ss who are assumed to encode auditory-verbally, should perform better than E Ss under spatial interference. This should result in an Instructions by Interference interaction.

In the C group, Ss have to memorize 3 discrete words while E Ss, given effective instructions, have only to remember one integrated stimulus figure that they can read out at recall. Overall recall performance should be superior in the E group, in accordance with findings of Murdock (1961) who demonstrated that, in the same paradigm, single words were far better retained than consonant trigrams.

Both effects should be more pronounced at 18 sec. than at 6-sec. intervals. The verbal interference condition in the C group should replicate Murdock's (1961) and Peterson and Peterson's (1959) results concerning retention of 3-item strings.

Method

Subjects. The 20 volunteer Ss from introductory psychology courses at Iowa State University were assigned to each of the instruction conditions according to a prearranged random schedule with the restriction that the ratio of males to females must be constant across conditions. There was an equal number of males and females in each group.

Materials and procedure. The words making up the 3-item string to be recalled were selected from the following set of direction words: "up, down, right, left, in, out". They were selected with regard to the spatial properties of the figures they describe. The 16 3-word strings were drawn randomly from the 24 possible strings which describe a 3-element stimulus figure extending in all 3 dimensions (Table 4, Appendix A). Each of the 16 strings was used in both interference conditions. The direction words were tape recorded for auditory presentation at a 2-sec. rate.

Two seconds prior to the first word of a string, Ss heard the word "Ready". A three-second interval followed the last word of each string. At this time Ss were cued for the interference tasks. The verbal interference task consisted of shadowing words presented auditorily from the tape recording at a 1-sec. rate. The words were a random selection of nouns with A and AA ratings from the Thorndike-Lorge (1944) word book. The cue for the verbal interference task was simply the presentation of the first noun to be shadowed.

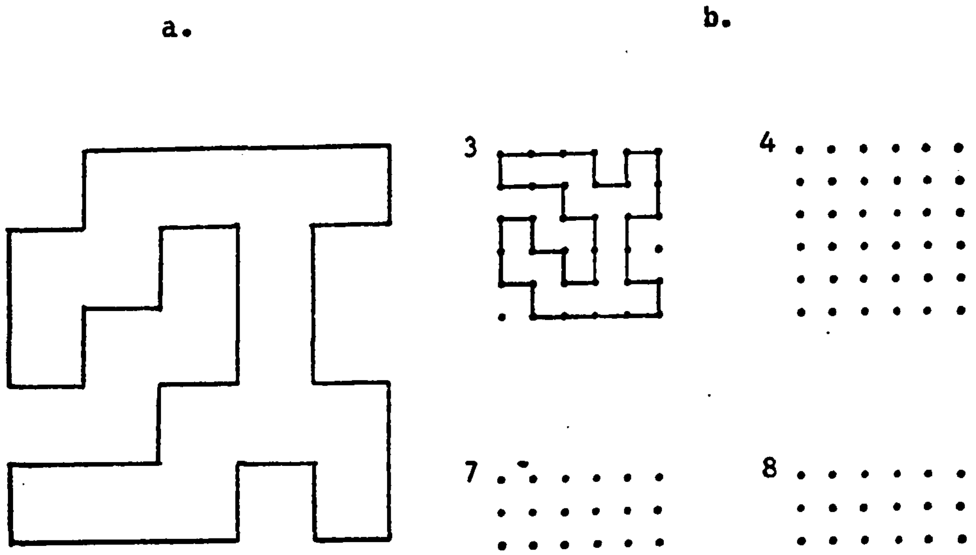

Figure 4. Spatial interference task, Experiment II, a. to-be-copied drawing, b. drawing copied correctly into dot matrix (a. and b. original size).

A tone signaled the beginning of the spatial interference interval and served as cue for S to turn over the topmost card in a stack of 3 by 5 inch file cards. On the cards were drawn nonsense figures composed of straight lines and connected with right angles (Figure 4a). The S's task was to copy these figures upside-down into a matrix of points such that the corners of the figures matched points in the matrix preserving the proportions of the figure. Figure 4b shows a correct copy of the line drawing in Figure 4a. No S was able to carry out this task correctly and completely in the course of the 18-sec. interval. This distractor task was similar to the one used by Brooks (1968). However, instead of his block-letter diagrams, nonverbal material was used in an attempt to minimize verbal interference. It also appeared desirable to have a scorable record of S's performance in the spatial interference task. The inclusion of a very similar task in the Newcastle Spatial Test (see e.g. Vandenberg, 1969) and the observation by French (1951) that pattern copying loads on space factors support the assumption that the present task is suitable for producing spatial interference.

Either 6 or 18 seconds after the beginning of the interference interval the word "Go" signaled the start of the 7-sec. recall interval. The sequence of types and durations of delays was randomized with the restriction that no repetition of a stimulus would occur with a lag of less than four.

Each S was tested individually. The experiment was introduced as being about memorizing instructions. Subjects who were assigned to the E condition were read the spatial encoding instructions cited on page 10. Immediately afterwards they received the following instructions, which were the same for C _S_s, except where stated otherwise.

> You'll hear a recording of short lists of words. Each list will have 3 words, corresponding to figures with 3 lines. (The last sentence was replaced for C _S_s by: "Each list will have 3 words, selected from among the following 6: 'up, down, right, left, out, in'. I want you to listen to the words and to repeat each list after a delay of several seconds. It is important that you keep the words in each list in the order you heard them.) Each list is preceded by the word "Ready". Whenever you hear "Ready", you know that a 3-word list will follow. After each list there will be a delay before you repeat the words of the list. You will be asked to do either one of two different tasks during this delay. Both are designed to make remembering a little difficult. Number one: You'll hear simple, familiar words during the delay. I want you to listen to these words and to repeat each word aloud, immediately after you hear it. Try not to miss any of them. This goes on until you hear your signal for recall of the direction words. Your recall signal is the word "Go". Or, number two: After the 3 direction words you'll hear a beep. Turn over the topmost card (demonstrate) and start copying the figure you find on this card upside-down into this dot matrix. (At this point in time _S_s are handed a sheet for practice and one for the experimental trials, see Figure 4. The latter sheet contained four more dot matrices than necessary, in order to prevent _S_ from anticipating the type of task in the last interference interval.) Do it as fast as possible but make sure that each corner of the upside-down drawing hits the corresponding dot (demonstrate). Stop copying when you hear the word "Go" and repeat the three direction words. While you are copying, you'll again hear words from the tape recording. Try to ignore them as best you can. Before we start the experiment, you'll get several practice trials to familiarize yourself with the task. Do you have any questions? Would you now please tell me in your own words how the experiment is going to go, so I know you got the idea.

After the six practice trials the tape recorder was halted in order to clarify any questions, S might have.

Analysis. One point was scored for each string recalled completely and in correct order. The data were analyzed in a 2 x 10 x 2 x 2 (Instruction by Subjects by Interference by Duration) analysis of variance.

Results and Discussion

As predicted, the two interference conditions affected the E and C Ss differently, $F(1,18) = 12.49$, $p < .001$. The summary of the analysis of variance of the error scores is presented in Table 2. Experimental Ss made more mistakes under spatial interference than did control Ss. The opposite tendency was found in the verbal interference condition (Figure 5). The spatial interference data are compatible with the hypothesis that mental images may not persist but instead are reconstructed on the basis of another, most likely verbal code. The higher error rate for E Ss may reflect just that. However, the verbal interference data are clearly incompatible with this view. Assuming a verbal basis for regeneration of the spatial images, one must expect that such a memory code is affected by verbal interference in much the same way as the code used by C Ss. In addition, the cognitive load connected with the recoding operations should result in further raising error scores.

Table 2. Summary of analysis of variance of errors, Experiment II.

Source of variation	Degrees of freedom	Mean squares	F values
Instruction (Inst)	1	0.3062	0.337
Ss	18	0.9083	
Interference (Intf)	1	2.0250	7.026*
Inst x Intf	1	3.6000	12.492***
Intf x Ss	18	0.2881	
Duration	1	0.8999	8.938**
Inst x Duration	1	0.1000	0.993
Duration x Ss	18	0.1006	
Intf x Duration	1	0.3062	1.604
Inst x Intf x Duration	1	0.1562	0.818
Residual	578	0.1909	

* $p < .05$
** $p < .01$
*** $p < .001$

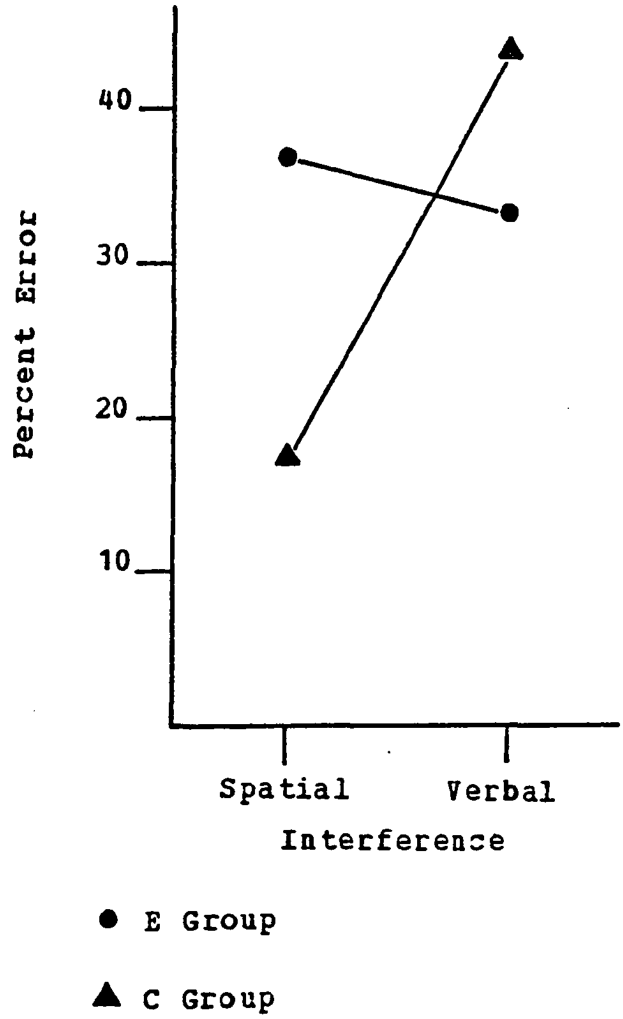

Figure 5. Percent error under spatial and verbal interference.

If a verbal code is excluded as the substrate of storage, the most likely alternative appears to be a spatial-relational code.

It might be suspected that the higher error scores of E Ss in the spatial interference condition were due to their working harder at the spatial interference task and not to modality-specific interference. However, an analysis of the figure copy output of both groups reveals that they produced a similar quantity. The number of corners drawn by each S during his 16 spatial interference intervals were counted. On the average, E Ss produced 73.4, C Ss 92.6 corners. This difference is not reliable, $t(18) = 1.70$. It is concluded, therefore, that the difference found in the spatial interference condition is due to the intended experimental manipulation.

The predicted overall recall superiority of the E group was not obtained (Table 2). This would argue against the hypothesis that spatial coding involves chunking of elements into unified entities, analogous to Murdock's (1961) demonstration that 3-letter words are considerably better retained over comparable intervals than are CCC trigrams. However, several factors might have prevented any recall advantage due to chunking from being discernible in the present experiment. With very few exceptions, E Ss commented spontaneously on their being unfamiliar with this kind of task and on its anticipated or experienced difficulty. No such complaints were voiced by C Ss, except for comments concerning the interference manipulations. This might indicate greater difficulty of the spatial encoding task, possibly due to the necessity of expending more cognitive resources for initial learning. Further, some Ss spontaneously discovered ways of spatially encoding the stimulus material and one S reported having used both, auditory-verbal memory after the 6-sec., and predominantly spatial imagery as a basis for recalling after the 18-sec. interval. He made only one mistake in each interference condition. Also, in the E group not all Ss may have followed the instructions consistently. The rather high error rate for E Ss under verbal interference suggests a verbal component in these Ss' memory representations. However, it is difficult to estimate just how large this component may be since there was a greater overall number of errors in the verbal interference condition, $F(1,18) = 7.03$, $p < .05$.

Although there are several procedural differences, the data of the control group in the verbal interference condition could be expected to replicate the results obtained by Murdock (1961) for retention of word triads. For the 6-sec. interval Murdock found that 39 % of the word triads were recalled correctly (s = 23 %). In the present study it is 43.8 % (s = 15.4 %). However, for the 18-sec. interval, Murdock found 23 % correct recall (s = 16 %, n = 24), while retention in the present study is 46.9 % (s = 21.4 %), a difference reliable with $t(32) = 3.18$, $p < .01$. This failure to replicate might be due to the persisting availability of memory for imagery, invented spontaneously by Ss. In Murdock's experiment this factor was not present since he used 3-letter words selected from the most frequent Thorndike-Lorge words instead of the more suggestive direction words.

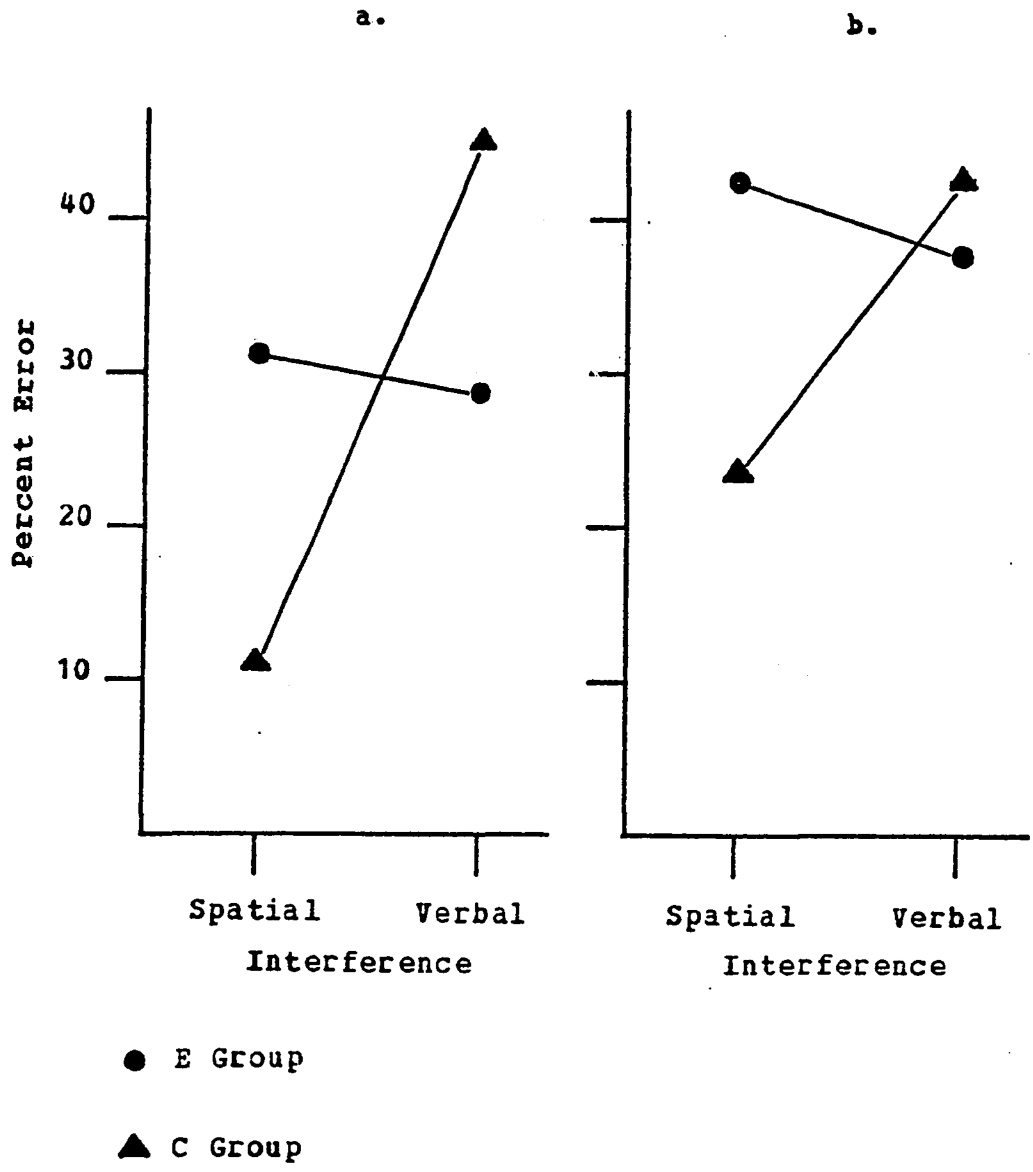

Figure 6. Percent error under spatial and verbal interference, a. 6-sec. interference interval, b. 18-sec. interval.

Figure 6 shows the Instruction by Interference interaction separately for the two retention intervals. It is apparent that the longer interval reduces overall retention, $\underline{F}(1,18)$ =

8.94, $p < .01$. Counter to expectations, at 18 sec. the difference between the E and C group under verbal interference is smaller than at 6 sec. and does not reach significance as it does at 6 sec. with $t(18) = 2.35$, $p < .05$. This appears to be due almost exclusively to higher recall of the C group, for the possible reasons already mentioned.

EXPERIMENT III

If Ss encode the verbal stimulus material under spatial instruction conditions in terms of an integrated, imagined figure, this could be regarded as one kind of chunking (Miller, 1956). That chunking occurs in the visual-perceptual mode is suggested in work by deGroot (1965). He found that chess masters were able to reconstruct a legitimate chess position almost perfectly after viewing it for only 5 sec., while less highly rated players were considerably less proficient at this task. Assuming a memory span of between 5 and 7 chunks (Miller, 1956), one chunk must contain 4 or 5 pieces on the average in the recall of a constellation with, say, 25 pieces. Chase and Simon (1973) replicated deGroot's findings, their evidence suggesting that the chunks are typically local clusters of pieces of the same color that usually defend each other. Thus, the relevant clustering dimensions appear to be visual as well as spatial-relational. The latter dimension may well be the most important, since after about an hour of practice an experienced chess player achieved the same recall performance if instead of a chess board he was presented with a diagram which represented the pieces by capital letters (Chase & Simon, 1973). Remembering a chunk should be about equally difficult regardless of the number of elements in the chunk. In other words, a stimulus figure consisting of three elements should be retained as easily as a five-element stimulus figure, provided the information content does not exceed the limits of what can be incorporated into a chunk. Experiment II did not support the chunking hypothesis since recall was not higher in the spatial instruction condition than in the control condition.

Experiment III was designed to provide a stronger test of the chunking hypothesis. The Ss were presented with an 8-item paired-associate list which they were to learn to a criterion of 3 subsequent perfect trials by means of the anticipation method. Each paired-associate item had a noun as stimulus term and as a response term had a string of direction words, selected from the following set: "up, down, right, left, out, in". The stimulus nouns were selected for high concreteness, high meaningfulness, and low frequency, in order to facilitate list learning. The Ss were instructed to form spatial images of the direction words. Half of the response terms were 3-element stimuli, the other half were 5-element stimuli. Pairing with stimulus terms was counter balanced. If the instructions induced Ss to spatially encode all response strings, there should be no difference in the number of trials to three subsequent correct recalls for individual 3-element and 5-element stimuli.

Method

Subjects. The 6 *S*s were volunteers from introductory psychology courses at Iowa State University.

Materials and procedure. The 8 stimulus words of the paired associate list were selected from the Paivio, Yuille, and Madigan (1968) norms. All words fulfilled the following criteria: Concreteness > 6, meaningfulness > 5, frequency < 10. The response terms were strings of direction words, selected to represent the figures described in Table 5, Appendix A. Each *S* was tested individually. The *S*s received the standard spatial imagery instructions and then the following additional instructions, specific to the paired-associate task:

> Each figure you will learn has been given a name. Your task is to learn the figure that goes with each name, so that you can give me the directions describing a figure when I give you its name. Always report the directions in a forward manner as I gave them to you. E.g. if the name of this figure (show model in Figure 1) was "hurricane" and I said to you "hurricane", you would repeat: "left, down, out, left". "There will be 8 such name-figure pairs. At first, I will give you each name with its corresponding figure once. Then I'll only give you the name and have you repeat the directions of the figure that go with it. After you have tried to describe the figure I'll give you the correct description again. We'll go through all the word-figure pairs as often as is necessary for you to learn the pairs completely and remember them reliably. Do you have any questions?

First, the entire stimulus list was read once to the *S*s. After the reading of each stimulus term the direction words were read at a 3-sec. rate, followed by a 10-sec. silent interval which was to give S the opportunity to construct the spatial stimulus, link it with the stimulus term, and do whatever might be appropriate for memorizing.

In each of the following trials E read a new random permutation of the original sequence. After the reading of the stimulus term there was a 10-sec. recall and anticipation interval. If Ss produced the correct response, i.e., all direction words in the same order as presented, they received verbal reinforcement without repetition of the response string. Reinforcement consisted of E's saying "that's it" when S first produced the correct response to a stimulus, and on subsequent correct responses E simply said "Yes". If the answer was incorrect, the string of direction words was repeated at a 3-sec. rate with a 10-sec. silent interval following.

Analysis. For each S the number of trials to criterion were averaged for 3-element items and for 5-element items, respectively. These scores were compared by means of a *t*-test for paired samples.

Results and Discussion

The hypothesis that 3-element and 5-element items were learned and remembered with equal ease had to be rejected. Items with 3-element responses needed fewer trials to criterion than items with 5-element responses (5.42, 6.58), $t(5) = 3.72$, $p < .05$. However, there were substantial individual differences in the overall rate of learning. The fastest S reached the first of three subsequent perfect trials after 5 trials, the slowest S after 10 trials. There were also reports by some Ss that they had difficulties adapting to the unfamiliar task of spatial imaging and that they first tried verbal memorization. It appeared that it was these Ss who took longer to accomplish the learning task. Consequently, there was the possibility that to the extent that Ss relied on verbal encoding there emerged differences in the learning rate between 3- and 5- element items. To the extent that verbal encoding was used, it would be expected that overall speed of learning was reduced, since it would be much harder, if not impossible in the time available, to form well integrated, verbally encoded chunks on the basis of the list material. Thus, speed of learning should be correlated with the difference in learning rate for the two levels of item complexity.

For each S, the number of trials to criterion was determined for each individual item. These values were averaged for the 3- and the 5-element items separately. The difference between these two averages was computed for each S. The difference scores were correlated with the overall number of trials to criterion; the number of trials it took for all eight items to be learned to three successive correct recalls. The resulting correlation was $r = .87$, $df = 4$, $p <$

.05. Since it cannot be determined to what extent the assumption of independence of errors is violated in computing this correlation coefficient, it should be treated as a descriptive statistic. On this level it indicates clearly, however, that those Ss who learned faster also showed less difference in learning time for the two kinds of items. The two fastest learners showed an average difference of .5 and 0.0 trials, respectively, for learning 3-element vs. 5-element items. Apparently, the more Ss made use of spatial encoding, the more they integrated the stimulus words into chunks, and the more efficient was their learning.

Experiment III also demonstrated that Ss are able to learn spatial information and retain it on a long-term basis. After reaching criterion, five of the six Ss were asked to recall the stimulus figures backward. Four Ss recalled all eight figures error free, and the fifth S made only one mistake. For some of the figures the time between Ss' last forward recall and final backward recall well exceeded one minute. Backward recall was rather fluent, suggesting that spatial readout, rather than a two-step verbal transformation, was involved in recall.

EXPERIMENT IV

The results of Experiment III suggest that Ss are able to retain information in spatial form for at least one minute. Further, other, informal, experiments conducted by the author indicate that spatial information can be stored with little decrement over a period of time of at least a month.

Experiment IV was designed to formally investigate retention of spatial information over a one-week period. It was hypothesized that at the end of this period spatial information could be retrieved and manipulated in ways not anticipated at the time of encoding. In the context of this experiment, Ss were expected to be able to remember individual spatial stimulus figures and combine them to form new composites at the end of the retention period. In order to identify spatial stimulus figures without reference to their specific spatial properties, which might spuriously enhance retention, Ss learned a list of paired-associates with strings of direction words (selected from the set: Up, down, left, right, in, out) as responses and words of high concreteness and low intralist similarity as stimuli.

There were two conditions of instruction. In the spatial instruction (E) condition Ss were asked to imagine spatial figures (p. 10) on the basis of the string of direction words which served as responses. Recall was to be based on a readout of the imagined figures. The list of four paired-associate (PA) items was learned by means of the anticipation method to a criterion of 3 subsequent perfect trials. The Ss in the control condition (C) received standard verbal learning instructions. Since Experiment III indicated that there are considerable individual differences in speed of acquisition under spatial visualization conditions, the control Ss were yoked with the experimental Ss. For each E S there was a C S with an equal number of anticipation trials to control for differences in study opportunity. Presentation of the list material was identical for both groups.

Half of the Ss in each instruction condition were tested immediately after list learning, the other half received the same tests one week later. The Ss were first presented with the stimulus names of the PA items and tested for recall of the response terms. On the basis of Experiment III it would be expected that to the extent that Ss use spatial encoding they learn the PA list more efficiently and have better immediate retention. Consequently, E Ss should show better recall than C Ss. This superiority of the E group should be more pronounced after one week, since four-item response terms that have high similarity should suffer more from intralist interference than the integrated spatial figures.

Besides the predicted main effects of instruction conditions and delay, there should be an Instructions by Delay interaction, due to more forgetting in the C condition.

Failure to perform in the PA recall task may be due, in part, to loss of the S-R associations. Therefore, Ss were asked to free recall the response terms in a second test. To the extent that free recall would surpass PA recall, spatial information would be available but not accessible through the stimulus cues. Free recall scores were expected to follow the same general pattern as PA scores.

Following free recall, Ss in the E condition were asked to retrieve pairs of responses, designated by E in terms of the corresponding stimulus names, and to mentally combine them to form a composite figure in a way specified by E. The Ss were then asked a number of questions about the composite figure. The questions were designed in such a way that they could be answered correctly only on the basis of the spatial properties of the composite figures, e.g. "How many lines are there that extend in the horizontal, vertical, depth dimension? How many points are there where just one line starts or ends? How many points are there where exactly 2, 3, 4, 5 lines meet? How many points are there in total? How many closed loops are there, with how many lines in each loop?" Those Ss who failed to answer any one of these questions correctly were asked to describe the spatial figures they actually used. The final test for both the E and C groups consisted of a multiple choice recognition test. No predictions were made about the relative performance of Ss in recall and recognition, since failure to recognize may be due to Ss' codes of the spatial information being too dissimilar from the spatial representations displayed in the recognition test. This would be reflected in terms of the number of spatial figures that are recalled but not recognized.

Method

Subjects. The Ss were 24 volunteers from introductory psychology classes at Iowa State University who received course credit for participation. They were assigned to the four treatment combinations of Delay and Instruction according to a prearranged random schedule with the restriction that the ratio of male to female must be constant across conditions. There were four females and two males in each Instruction - Delay treatment combination.

Materials and procedure. The 4 stimulus words of the paired associate list were selected from the Paivio, Yuille, and Madigan (1968) norms. All words fulfilled the following criteria: Concreteness > 6, meaningfulness > 5, and frequency < 10. The response terms were strings of 4 direction words, selected to represent the figures described in Table 6, Appendix A.

Each S was tested individually. The E Ss received the standard spatial imagery instructions and then additional instructions specific to the PA task. These were the same instructions as those used in Experiment III, except for mentioning 4 name-figure pairs instead of 8, asking S to describe the procedure of the experiment in his own words, and the following admonition to E Ss: "There is one thing I should mention. The most important point in this experiment is for you to base your recall on the figures you remember and not on words."

The list material was tape recorded for auditory presentation. The Ss first heard the entire list once. Three seconds after the stimulus term, the direction words were presented at a 3-sec. rate, followed by a 10-sec. silent interval which was to give Ss the opportunity to construct the spatial stimulus in the E group, or to organize the response string in any way in the C group, and link the S and R terms. During each of the following trials all items were tested in random permutations of the original sequence. After presentation of the stimulus term there was a 10-sec. recall and anticipation interval. Recall was recorded by E. After the interval the string of direction words was repeated at a 3-sec. rate, followed by a 10-sec. silent interval which provided an opportunity for Ss to memorize the material. The presentation of the list material in the E condition was terminated upon Ss' reaching a criterion of 3 subsequent perfect trials. Each S in the C group was yoked with one S in the E group on the basis of the number of anticipation trials presented.

All *S*s signed up for the experiment under the impression that they would participate in two experimental sessions, one week apart. However, the immediate test group *S*s were excused at the end of the first session and asked not to talk to fellow students about this aspect of the experiment. This was done in an attempt to prevent bias in the composition of the groups due to self-selection and to avoid speculation about the nature of an experiment that would require some *S*s to participate in only one but other *S*s in two sessions. The experiment was introduced as being concerned with the effects of interference on the learning of directions and that in the second session they would be given an interference test to see how their "learning today" would affect new learning to take place in the session one week later.

In the immediate testing condition testing began one minute after the last learning trial. For the PA recall test a new random permutation of the stimulus terms was presented and *S*s were to verbally recall the corresponding response strings. The combination test consisted of a number of questions (Table 7, Appendix A) the answers to which were weighted equally. In the recognition test each correct item was presented together with 3 distractors. Presentation in the E group was in terms of perspective line drawings of the stimulus figures with black lines on white background (Figure 8,

Appendix A). In the C group the correct string of four direction words was presented together with 3 incorrect 4-item strings. The strings were typewritten on 3 by 5 inch file cards.

Analyses. One point was scored for each direction word recalled in the correct position, in both the PA and the free recall tests. In the combination test, one point was scored for each correct answer and, likewise, one point for each correct identification in the recognition test. It was intended to analyze the recall scores in a 2 x 2 x 6 x 2 (Instructions by Interval by Subjects by Recall Mode) analysis of variance with yoked pairs as observational units. However, since there was severe inhomogeneity of variance with zero variance in some cells, this analysis could not be carried out meaningfully. Where possible, the scores from the combination and recognition tests were compared by means of t-tests across intervals and only within instructions conditions. The data of an additional S were included in each, the E and C delayed testing groups. These additional Ss were run in order to make up for possible attrition of the originally scheduled Ss, but were not needed for this purpose. One E S was not available for enough time at the testing session for the administration of the combination test.

Results and Discussion

Initial learning. Since Ss were randomly assigned to treatment conditions, no difference was expected in speed of acquisition for groups receiving the same treatment during initial learning. The E group to be tested one minute after reaching criterion, took 12.17 trials to criterion (TTC), the E group to be tested after one week needed 11.71 TTC, $t(11) = .24$. A trial consisted of presentation and recall attempts of all four items, in a random sequence. There was also no significant difference in TTC between the two corresponding C groups (9.67, 10.14; $t(11) = .30$).

The lower numbers of TTC for C Ss reflect a systematic bias. The yoking of C with E Ss was planned under the assumption that C Ss would take longer to reach criterion than E Ss, consistent with the results of Experiment III. If, in a yoked pair, the C S should happen to learn faster, it was hoped that he might tolerate some additional trials beyond criterion performance. Counter to these expectations, only in 7 out of the 13 pairs in Experiment IV did the C Ss need more or an equal number of TTC. In two cases C Ss reached criterion by 6 trials faster than their E counterparts. It proved to be unfeasible to sustain Ss' motivation to attend to the tape recording for still more trials after they had already recalled all items perfectly three times in a row. Initial learning was therefore stopped after C Ss' reaching the criterion of three subsequent perfect trials. Considering the difficulties involved in using the TTC measure as baseline for estimating retention (e.g. Underwood, 1964), half of the _S_s in each instruction condition were tested initially, 1 min. after reaching criterion. It was hoped that this would provide a baseline for measuring retention after one week.

Paired-associate and free recall. One week after learning the four-item PA list, E _S_s recalled 73 % of the direction words in their correct positions in the PA test and 88 % in the free recall test. However, this difference was not significant, $t(6) = 2.28$. The corresponding scores for the C group were 64 % in PA recall and 67 % in free recall. These and the data from initial testing are summarized in Figure 7, the raw data are listed in Table 11, Appendix C. The intended analysis of variance could not be carried out, since there was severe inhomogeneity of variance, with no variance at all in the initial free recall of the E _S_s, due to perfect performance.

Comparisons of E and C scores by means of _t_-tests are ruled out because of the systematic bias in the C group data. Thus, these data are not interpretable in terms of the experimental hypotheses.

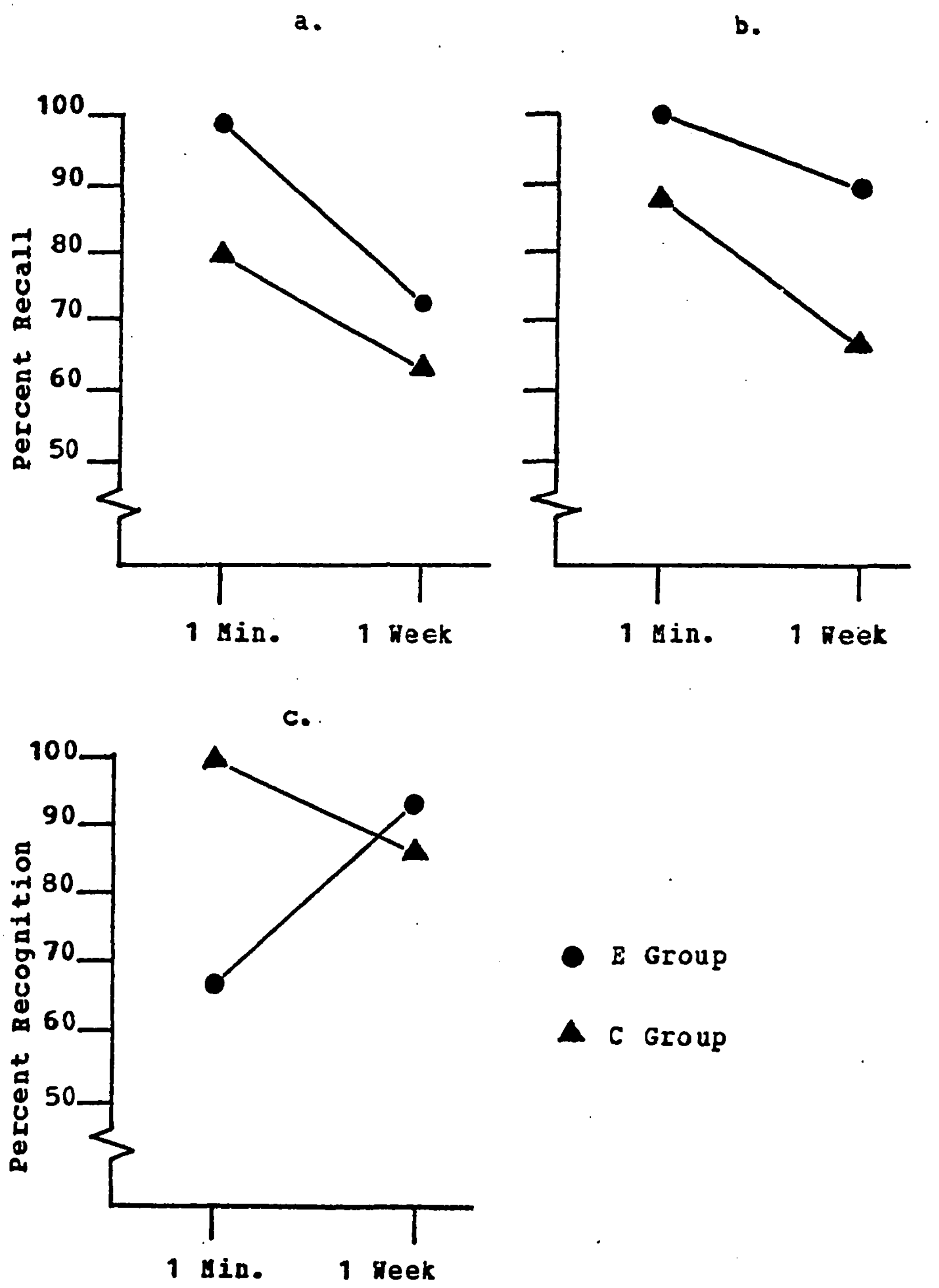

Figure 7. Test performance after one minute and after one week, a. PA recall, b. free recall, c. recognition

Although there is apparently high retention in the E group over a one-week interval, it can not be concluded that it is specifically spatial information that is retained. The experimental Ss might recode the initially acquired spatial information into a verbal-linguistic representation and use it as a basis for recall after one week or as a basis for reconstructing the spatial code if the recall task requires recourse on the spatial properties of an item, as e.g. in the combination task. Due to the bias in the C data, lower retention in this condition cannot be attributed to a less efficient verbal-linguistic code. The control group thus does not serve its purpose: to show that retention at the level attained by the E group is not possible on the basis of a verbal-linguistic representation.

A further complication in interpreting the present data arises from Ss' considerable flexibility in handling the PA learning task. At the end of the testing sessions in both C groups, Ss were asked how they went about memorizing the PA list. Without exception, the Ss with above average recall reported visualizing the material. A favorite example cited by Ss was the item with the stimulus term "Avalanche". Subject # 21 imagined "swings in skiing" together with Avalanche, likewise S # 15. Subject # 10 reported visualizing the path of an avalanche. One S (# 28), who recalled below average, related the direction words to the face of a clock, which he said worked fine for "up-12", "left-9" etc. but not very well for "in, out".

Several suggestions for further experimentation can be derived from these outcomes of Experiment IV. First, it appears necessary to provide for a longer PA list, so that proactive interference has more opportunity to build up in the C condition. This would require more than a 1-hour experimental session. Second, familiarization with the task could be achieved in a pretraining session, during which Ss in the E group would gain facility with spatial imaging, while C Ss would learn a PA list which is not conducive to using imagery as a mediation device, thus giving Ss in this group a set for verbal processing. The experimental list itself should contain stimulus terms that are highly available, discriminable, and not conducive to using imagery. A simple way to achieve this might be to select as stimulus terms the digit words "one" through "nine".

Recognition. The results of the recognition tests are summarized in Figure 7. All group averages are significantly above chance level (25 %). The smallest difference from chance (42 % for E Ss at immediate testing) is significant with $t(5) = 2.72$, $p < .05$. All other comparisons are nonsignificant. An analysis of variance could not be performed on these data, since there is considerable inhomogeneity of variance, with no variance at all in the C group tested after 1 min.

It would appear to be worthwile to include the recognition tests in a replication of the present experiment, which was changed along the lines suggested above. If a significant increase in recognition performance over time would be found in the E condition, it would be interesting to interpret such a finding in the context of the controversy surrounding the Gestalt theory hypothesis that traces of memory for form undergo autonomous change over time (Riley, 1962).

Combination test. The reliability of the 22-item combination test was estimated by means of the Kuder-Richardson formula 20, $r(tt) = .81$. The 11 questions for each composite can be treated as parallel test forms and the correlation between the scores on composite 1 with the scores of composite 2 would be an estimate of parallel test reliability. For the present 11-item tests this estimate was $r(kk) = .39$. Adjusted for a test length of 22 items by means of the Spearman-Brown formula, $r(kk)' = .56$. This is likely to be an underestimate, since Ss were unfamiliar with the task and might have shown a more stable performance after more practice. To what extent a practice effect might have been present, is not clear, since the order of composites was not counterbalanced. The higher scores on the second composite might be due to differences in item difficulty besides any practice effect (58 %, 67 %), $t(10) = 2.61$, $p < .05$.

The combination test was used as a measure of spatial imagery on the basis of face validity. If performance on the combination test was based on the processing of spatial information, covariation with the other measures used would suggest the presence of spatial components in the performance of Ss on these measures as well. For the immediately tested E group, a correlation of $r(4) = .89$, $p < .05$, was obtained between recognition and combination scores. There was a non-significant correlation between PA recall and combination test performance for the E group tested after a week, $r(4) = .65$. In the same group, free recall correlated with combination test performance with $r(4) = .95$, $p < .01$. These data support the hypothesis that performance of E Ss in both, the immediately and after one week administered tests, was based on spatial information. However, the small number of test items as well as the small number of Ss does not allow for very stable estimates of reliability and validity of the combination test. The above conclusion can thus not be a strong one.

GENERAL DISCUSSION AND CONCLUSION

The four experiments reported here attempted to show the existence of a memory code which is distinct from visual and verbal codes. Further, it was attempted to demonstrate that this nonvisual, nonverbal code allows for processes of storage, organization, and retrieval to occur, as well as for complex manipulations of information.

In Experiment I, E Ss' superior performance in the backward recall task indicates that their internal representations of the strings of direction words had properties not possessed by the C Ss' representations, which is what the experimental manipulation had intended. That these properties of the E code were not the result of a more efficient verbal code is suggested by the differences in resistance to the two kinds of interference used in Experiment II. Better recall of E than C Ss under verbal interference with the opposite order obtaining under spatial interference would be inconsistent with any assumption of both, E and C groups, using the same representational system. Further, the results of this experiment indicate greater permanence of the code used by E Ss than is found in studies investigating visual sensory memory. Even the 5-sec. estimate for iconic memory duration under optimal conditions, with dark pre- and post-exposure fields (Averbach & Sperling, 1968), falls short of the present retention durations. While Sperling's procedure was designed to avoid any interfering influences, the present Ss were tested in a fully lit room and recalled after 6 or 18 seconds of performing an interfering task. Posner, Boies, Eichelman, and Taylor (1969) estimated the duration of visual short-term memory from differences in reaction time between physical and name matches of pairs of visually presented letters and found it to have decayed after around 1.5 seconds. Phillips and Baddeley (1971) criticized the former study for not considering that the development of a name code may mask the persisting visual code. Using pairs of patterns in a 5 x 5 matrix, to be matched after intervals of differing durations, they found recognition performance still declining after three and possibly up to nine seconds. They concluded that visual short-term memory can be maintained beyond three seconds but not beyond nine seconds. However, in the light of the present findings, their own results may be confounded by Ss' recoding of at least part of the stimulus information into a spatial representation on which the "same - different" judgment was based after exposure of the second pattern. Thus, their higher estimate of visual short-term retention may reflect the contribution of a longer lasting nonvisual code, possibly of the kind studied in the present experiments.

While there was an apparent rejection of the chunking hypothesis in Experiment III, due to the different learning speeds for 3- and 5-element responses, the secondary analysis provided an explanation for this difference and yielded results that are consistent with the hypothesis that strings of direction words were organized into chunks. The Ss who learned fastest overall were those with the smallest difference in speed of learning of 3- versus 5-element items. On an interpretive level this would mean that the more Ss treated the stimulus material as consisting of spatially extended, integrated figures, the more they benefited from the higher efficiency of the spatial code, an efficiency that is due, at least in part, to the smaller number of functional elements to be learned separately.

That spatial information is available for at least one week after learning is evident from the performance of E Ss on the combination test in Experiment IV. While it cannot be excluded that retention was mediated verbally, Ss must at least have retained the rules for regenerating the spatial stimuli and, in addition, some criteria for deciding whether regeneration had been accomplished successfully. The positive correlation between combination test scores with free recall scores in the E condition after one week supports the hypothesis that free recall was based on a spatial representation.

So far, the results of the four experiments appear to be quite consistent, and in good agreement with the major experimental hypotheses. However, several predictions remained unconfirmed. Since all predictions were based on the assumption that E Ss would follow instructions closely and that C Ss would not spontaneously discover the spatial encoding mode, deviations from the predicted results may be due to not meeting this assumption. If so, this would require that the results obtained be interpretable in terms of Ss' using verbal modes of processing when they were expected to encode spatially and vice versa. Such an interpretation appears to be plausible. The slower speed in backward than in forward recall for the E group in Experiment I can be explained as a result of some E Ss' using verbal memory, which does not affect forward but would slow down backward recall. No differences in overall performance were found in Experiment II between the two instruction conditions, counter to what would be expected if the E Ss integrated the direction words into a unified spatial figure. The rather high error rate of E Ss under verbal interference suggests that verbal memory was used as a basis for recall to a considerable extent, possibly as a consequence of Ss' not consistently using spatial encoding. Further, since retention of verbal material suffers greatly from an 18-sec. verbal interference interval, C Ss might have relied on imagery involving directions, as was suggested by comments of some Ss. This would explain the much higher than expected retention after 18 seconds under verbal interference in the C group. It would also tend to decrease differences between E and C recall, following the longer retention interval, thus explaining why the predicted effects were not stronger after 18 than after 6 seconds. The role of Ss' less than complete adoption of the E instructions in Experiment III and their unanticipated flexibility in using alternative processing strategies in Experiment IV have already been discussed. Thus, the failure to find some of the predicted results does not necessarily weaken the conclusions of this investigation. It must be kept in mind that the Ss were naive with regard to the experimental task and received only minimal pretraining at the beginning of the experimental session.

From pilot experiments it was evident that the task of imaging spatial figures, at least according to the E instructions, was highly unfamiliar to Ss. The experiments reported here confirmed this impression. Most E Ss commented spontaneously that they doubted initially whether they would be able to follow instructions at all, and that they had to fight the tendency to treat the stimulus material in verbal terms early in the experiment. This difficulty appeared to decrease rapidly with practice. There is evidence that tasks involving spatial abilities are highly trainable (e.g., Blade & Watson, 1955). One possibility to test whether the discrepancies between predictions and results were due to deviations from expected encoding strategies, would be to provide for more extensive pretraining of E _S_s with the spatial encoding task. Correspondingly, C _S_s could be given a mental set for verbal processing. A closer match of predictions with results should be found if these manipulations were added to the experimental procedures.

The lack of familiarity with the experimental task reported by _S_s might reflect a general neglect of the spatial-relational mode of representing information in the subject population. Information processing in this mode would then be a phenomenon rather peripheral to the understanding of cognitive processes. However, these difficulties might be due to the specific, _E_-determined, procedure of using the spatial mode. This would leave open the question of the function of a spatial memory. Apparently, it can serve as a link between the verbal and visual modalities. The spatial images, that _S_s constructed purely on the basis of verbal information, were well recognizable in terms of rather arbitrary visual representations (Figure 8, Appendix A). It may be asked to what extent a spatial-relational mode of representation, of the kind investigated here, would be involved in processes of cross-modal transfer in general, as well as in the closely related processes of intersensory integration of information. The existence of a "single integrating framework located in the central nervous system" that could handle information about positions of stimuli in space has been postulated by Fisher (1962, p. 321). Interference paradigms using interpolated tasks that specifically affect spatial processing may be appropriate tools for investigating these questions.

There is a scarcity of theoretical models that are useful in research on spatial information processing. An exception is the work of Baylor (1972). He took thought protocols of himself solving problems from one of Guilford's tests of spatial visualization, the Block Visualization Test. Based on a logical analysis of the thought protocols, Baylor found it useful to define two problem spaces, an S Space (Symbolic Space) in which certain symbolic operations are carried out, such as addition, and an I Space (Imagerial Space) in which mental images of spatially extended structures are manipulated. The I space has the interesting property of storing information about specific images and their components, while the S Space contains generic information.

If Ss construct and manipulate spatial representations in an I-type space, these representations must have certain properties of specific, spatially extended items, such as size. It appears possible to test this hypothesis with the stimulus material used here, by means of a method developed by Hayes (1973). Subjects would be instructed to visualize spatial figures with line segments of a certain size, e.g., as indicated by a visible scale. Subsequently, pictures of the same or slightly modified stimuli would be presented, varying in size. A minimum for reaction time in the "same-different" judgments, found in the vicinity of the target size, would indicate that the spatial images had the property of size and would thus support Baylor's notion of an I Space in which tokens of spatial-relational structures are constructed and manipulated.

Terms like "image" and "imaging" have been used occasionally in this report. It is recognized that these terms are freighted with an enormous surplus of denotations and connotations (see e.g., Bower, 1972; Holt, 1972; Pylyshyn, 1973). However, there was no need to conduct a semantic analysis in the present context, and usage of the "imagery" vocabulary was informal. For the purposes of this investigation, "imaging of spatial figures" can be conceived of as Ss' following E instructions and "spatial images" may be defined as the hypothetical products of this activity. Likewise, the use of the term "spatial" was not intended to define the nature of the representational system under investigation. This system may well be suited to represent relationships between elements in a more general manner, with spatial relations like "above, to the right of" merely being special cases.

Whether this system of mental representation is related to the psychological substrate of Monod's "imagined experience" remains an unanswered and possibly unanswerable question. However, nothing compels us to assume that thinking occurs within just one or the other representational system or code. It would appear highly unlikely that the manipulation of information, as far as thinking processes are concerned, is accomplished only, or even predominantly, in terms of its verbal representations. Language may not be a medium of thinking at all but rather a device for editing and emitting the results of operations performed on informational structures at various points on a continuum, or even network, of codes or mental representations. Such a continuum is not so speculative after all, since we are forced to assume the existence of coding processes intervening between the slow waves and action potentials of receptor output, representing a problem situation, and the structure of the sentences formulating its solution, so long as we think it necessary to assume that an effect has a cause.

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ACKNOWLEDGMENTS

I gratefully acknowledge the contributions of my doctoral committee which included Dr. Frederick Brown, Dr. David Edwards, Dr. Gerald Klonglan, Dr. Edwin Lewis, and Dr. Leroy Wolins.

In particular, I would like to thank Dr. Wolins for his thoughtful criticisms and his statistical advice. His professional and personal support throughout my graduate education will always be remembered and appreciated.

I am especially indebted to Dr. Wayne Bartz, my major professor. Granting me complete freedom to pursue my research interests and expressing almost unconditional confidence in my abilities, he challenged me. Being ready, whenever needed to advise, criticize, and be helpful in whatever way possible, he enabled me to meet his challenge.

The financial basis for my graduate education was provided by the Stiftung Volkswagenwerk, Hannover, W-Germany. I am grateful for their flexible and reliable support.

My colleagues on M-deck have contributed much to my research, serving as pilot subjects, discussants, and critics. Perhaps even more important was their friendship when circumstances were difficult. I wish to thank them for both.

APPENDIX A

Table 3. List of stimuli, Experiment I.

out, right, in, down
right, in, up
left, out, up
right, out, up, out
down, left, out
up, right, out
up, in, down, left
right, in, down, in
right, out, up
down, left, in, left
left, out, down, in
right, down, out
out, left, up
up, in, up, right
in, down, right
out, right, up
down, left, down, in
out, up, left
in, down, right, up
left, down, out, up

Table 4. List of stimuli, Experiment II.

v	18	right, up, in
s	18	down, out, right
s	6	left, down, in
v	6	left, down, out
v	18	left, up, out
s	6	down, in, right
s	18	right, out, up
s	6	up, right, out
s	6	out, left, down
v	18	right, in, up
v	18	down, in, right
s	18	left, up, in
v	6	up, left, out
v	18	up, right, out
v	6	in, down, left
v	6	right, out, up
s	18	left, in, down
s	18	right, up, in
s	18	left, up, out
v	6	out, left, up
v	6	left, down, in
s	6	up, right, in
v	18	down, out, right
v	6	left, in down
s	6	left, down, out
v	18	out, left, down
s	6	in, down, left
s	6	right, in, up
v	6	up, right, in
s	18	up, left, out
v	18	left, up, in
s	18	out, left, up

Column 1 refers to interference conditions: s = spatial, v = verbal.

Column 2 refers to duration of delay, either 6 or 18 sec.

Table 5. Paired-associate list, Experiment III.

Stimulus (A)	Response	Stimulus (B)
Avalanche	left, up, in	Tripod
Blister	out, up, left, in, up	Scorpion
Hardwood	right, up, out	Poster
Invoice	down, in, up, left, down	Missile
Missile	right, up, left	Invoice
Poster	right, in, down, in, left	Hardwood
Scorpion	up, left, out	Blister
Tripod	down, out, left, in, down	Avalanche

Each stimulus term occurs with both, a 3- and a 5-element response term in the two counterbalancing orders (A) and (B).

Table 6. Paired-associate list, Experiment IV.

Stimulus	Response
Avalanche	left, down, right, out
Hardwood	out, right, down, in
Poster	right, out, up, in
Tripod	out, left, out, down

Table 7. Combination test items, Experiment IV

How many lines are there that extend horizontally?
How many lines are there that extend vertically?
How many lines are there that extend in depth?
How many points are there where just one line ends (or starts)?
How many points are there where exactly two lines meet?
How many points are there where exactly three lines meet?
How many points are there where exactly four lines meet?
How many points are there where exactly five lines meet?
How many points are there in total?
How many closed loops are there?
How many lines make up the closed loop(s)?

Table 8. Recognition test items, Experiment IV.

1.

up, left, down, in

* left, down, right, out

right, in, left, up

out, left, down, out

2.

out, up, right, out

in, right, down, left

down, left, down, out

* out, right, down, in

3.

* right, out, up, in

in, left, down, out

in, right, down, in

left, out, up, right

4.

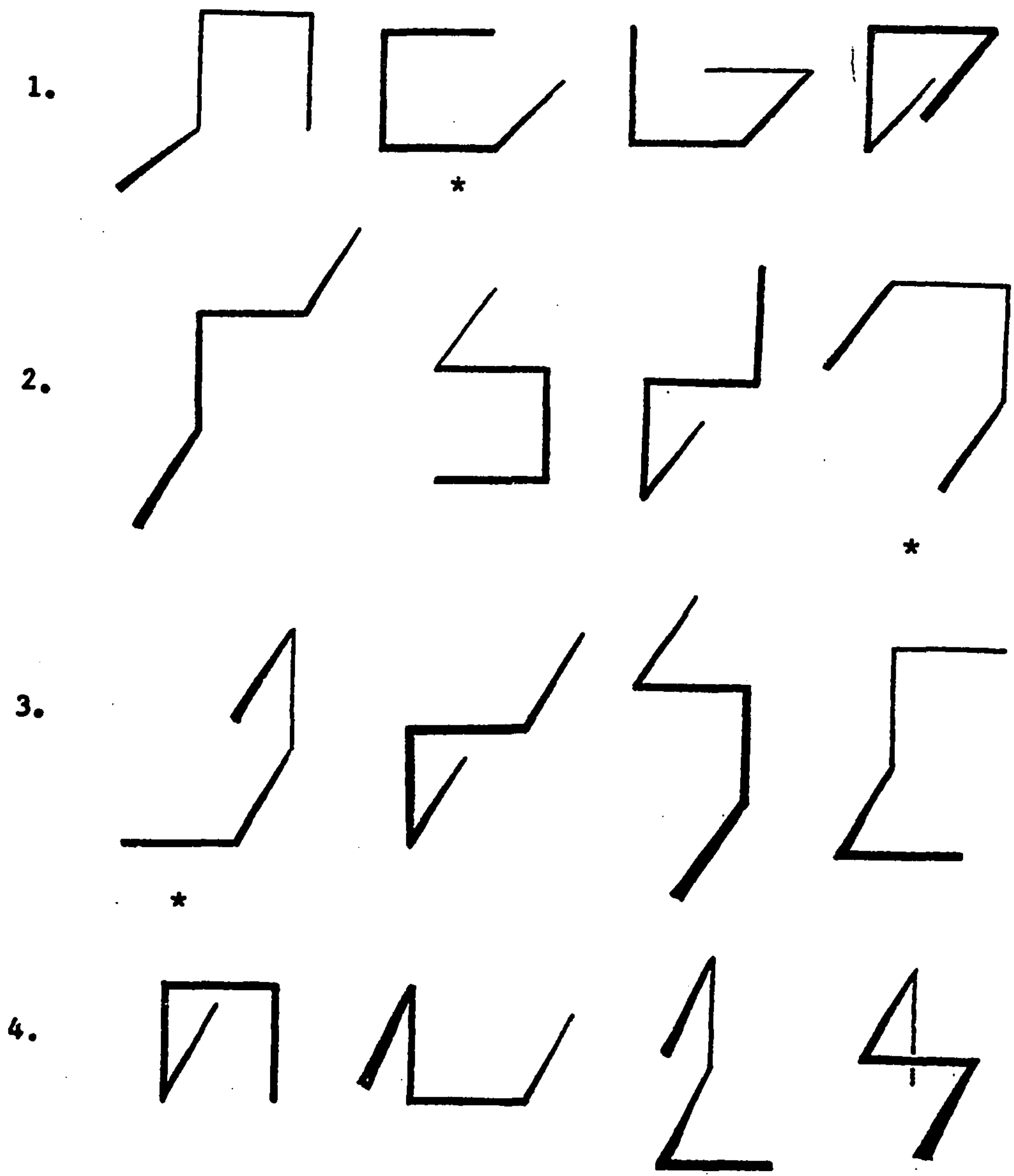
up, left, down, out

out, down, right, out

left, out, up, in

* out, left, out, down

* The asterisk marks the correct alternatives.



* The asterisk marks the correct alternatives

Figure 8. Recognition test items, E group, Experiment IV.

APPENDIX B

Table 9. Summary of analysis of variance of recall, Experiment I.

Source of variation	Degrees of freedom	Mean squares	F values
Instruction (Inst)	1	0.5281	1.452
Ss	14	0.3638	
Direction (Dir)	1	1.3781	15.831**
Inst x Dir	1	0.2531	2.908
Dir x Ss	14	0.0870	
Complexity (Com)	1	0.7031	3.987
Inst x Com	1	0.0781	0.443
Com x Ss	14	0.1763	
Dir x Com	1	0.0281	0.202
Inst x Dir x Com	1	0.0781	0.562
Residual	270	0.1390	

** $p < .01$

Table 10. Summary of analysis of variance of log latency, Experiment I.

Source of variation	Degrees of freedom	Mean squares	F values
Instruction (Inst)	1	1.02288	7.492*
Ss	14	0.13654	
Direction (Dir)	1	8.72673	134.342***
Inst x Dir	1	1.59557	24.563***
Dir x Ss	14	0.06495	
Complexity (Com)	1	0.04013	1.392
Inst x Com	1	0.00075	0.026
Com x Ss	14	0.02883	
Dir x Com	1	0.00001	0.0006
Inst x Dir x Com	1	0.05531	3.114
Residual	270	0.06101	

* $p < .05$
*** $p < .001$

APPENDIX C

Table 11. Raw data of recall and recognition tests, Experiment IV.

S #	PA recall	Free rec.	Recognition
Group E (1 min.)			
1	16	16	2
6	16	16	4
11	16	16	1
14	16	16	1
17	16	16	4
19	15	16	4
Group E (1 week)			
2	14	14	4
4	16	16	4
5	8	14	4
8	9	16	4
18	12	15	3
25	7	8	4
27	16	16	3
Group C (1 min.)			
7	12	12	4
10	16	16	4
13	7	9	4
16	16	16	4
20	16	16	4
21	10	16	4
Group C (1 week)			
3	12	12	4
9	5	6	1
12	13	13	4
15	16	16	4
22	10	10	4
26	8	11	3
28	8	7	4